REPORT DOCUMENTATION PAGE

AFRL-SR-BL-TR-98-

0181

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for revi~~ewing~~
the data needed, and completing and reviewing this collection of information. Send comments regarding this burden estimate ~~or~~
reducing this burden to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferso~~n~~
Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503

taining
is for
ice of

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE Feb 98	3. REPORT TYPE Final 11/01/94 - 12/31/97

4. TITLE AND SUBTITLE High-Frequency Properties of Two-Dimensional Josephson-Junction Arrays	5. FUNDING NUMBERS 61102F 2305/G9

6. AUTHOR(S) Christopher J. Lobb	

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) University of Maryland Center for Superconductivity Research Department of Physics College Park, Md. 20742	8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) Air Force Office of Scientific Research Bolling Air Force Base Washington, D. C. 20332-6448	10. SPONSORING / MONITORING AGENCY REPORT NUMBER F49620-92-J-0041

NE

11. SUPPLEMENTARY NOTES	19980218 035

12a. DISTRIBUTION / AVAILABILITY STATEMENT

APPROVAL FOR PUBLIC RELEASED: DISTRIBUTION UNLIMITED

13. ABSTRACT (Maximum 200 Words)

See attached

Niobium Josephson junction arrays show great promise as compact, low
dissipation, effecient sources of electromagnetic radiation at frequencies
from below 100 GHz to as high as 1 THz. Current small resistively shunted
arrays (containing 100 phase-locked junctions) are tunable over a broad range
and produce power which is within a factor of 3 of the theoretical maximum.
Unshunted arrays have also been made which are not tunable, but produce very
narrow linewidth radiation with remarkably high efficiency (conservatively
estimated at 15% from DC to 157 GHz). In addition, a new scanning probe,
based on SQUIDs (Superconducting QUantum Interference Devices) has been
designed and constructed, and is not in operation, yielding spatial images of
the magnetic field distribution in arrays.

14. SUBJECT TERMS			15. NUMBER OF PAGES 7
			16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT UNCLASSIFIED	18. SECURITY CLASSIFICATION OF THIS PAGE UNCLASSIFIED	19. SECURITY CLASSIFICATION OF ABSTRACT UNCLASSIFIED	20. LIMITATION OF ABSTRACT UL UL

DTIC QUALITY INSPECTED 3

I. COVER PAGE

II. ABSTRACT

Niobium Josephson junction arrays show great promise as compact, low dissipation, efficient sources of electromagnetic radiation at frequencies from below 100 GHz to as high as 1 THz. Current small resistively shunted arrays (containing 100 phase-locked junctions) are tunable over a broad range and produce power which is within a factor of 3 of the theoretical maximum. Unshunted arrays have also been made which are not tunable, but produce very narrow linewidth radiation with remarkably high efficiency (conservatively estimated at 15% from DC to 157 GHz). In addition, a new scanning probe, based on SQUIDs (Superconducting QUantum Interference Devices) has been designed and constructed, and is now in operation, yielding spatial images of the magnetic field distribution in arrays.

High-Frequency Properties of Two-Dimensional Josephson Junction Arrays

Christopher J. Lobb

Center for Superconductivity Research, Department of Physics
University of Maryland, College Park, MD 20742

A. Background

If compact, tunable, efficient sources of electromagnetic radiation were available in the millimeter to submillimeter range (roughly 100 GHz to above 1 THz), a large number of applications would be made possible, or reduced substantially in cost. Aside from the general advantages of opening up more bandwidth, potential applications range from secure satellite to satellite communication (by choosing a frequency which is heavily absorbed by the atmosphere), high-speed wireless communication (in "windows" of lower absorbtion), sources of radiation for characterization of sensors and for far-infrared spectroscopy of electronic materials, and local oscillators for single-chip integrated receivers.

Current sources at the lower frequency end include Gunn and IMPATT diodes. Although these devices may be frequency multiplied, efficiency and tunability are poor. Laser sources are available from the high-frequency end, but they are not tunable, they are large, and their power output is low.

Josephson junctions are good candidates for oscillators in this range; when a constant voltage V_{DC} is applied to a junction, a current results which oscillates at a frequency ν given by [1]

$$\nu = \frac{2e}{h}V_{DC} = \frac{483GHz}{mV}V_{DC}, \qquad (1)$$

where h is Planck's constant and e is the charge of the electron. Single junctions can emit radiation over the frequency range of interest, with a high fraction of the power supplied to the junction being converted to radiation. Unfortunately the power emitted by a single junction (about 1 nW in our junctions) is too small, and

the impedance is too low.

If an array with N_{TOT} junctions can be constructed in which all the junctions oscillate in phase and at the same frequency, the theoretical power coupled to an impedance-matched load scales with N_{TOT} [2]. Arrays with thousands or even millions of junctions can be made, but phase-locked behavior is not guaranteed. At the present time, however, great progress is being made both experimentally and theoretically toward making large phase-locked arrays [3]–[8].

B. Accomplishments

We have performed experiments with both overdamped and underdamped Josephson-junction arrays. The results show strong evidence of total synchronization (phase locking) for both types of arrays. Overdamped arrays emit radiation coherently in a broad frequency range (75 to 430 GHz with a maximum detected power of 0.15 μW at 210 GHz for a 100-junction array). Therefore, these devices are good candidates as tunable high frequency sources. Underdamped arrays show phase locking only at specific resonant frequencies (in the range 150 to 200 GHz). However, the estimated linewidth of their emitted radiation is as low as a few hundred hertz. In order to perform a more detailed investigation of the high frequency properties of the arrays, two more powerful experimental technique are also being implemented: scanning SQUID microscopy and irradiation with far infrared sources.

1) Overdamped Arrays: The junctions forming our overdamped arrays are shunted by an external molybdenum resistor. This feature makes the junctions overdamped, i.e. they have a non-hysteretic current voltage characteristic. This

type of junction offers a better voltage (therefore, frequency) tunability.

Several junctions connected together can operate in a coherent (synchronized) state: in this case the maximum power coupled to a matched load scales linearly with the number, N_{TOT}, of operating junctions according to:

$$P_{MAX} = N_{TOT} I_C^2 R/8, \qquad (2)$$

where I_C is the critical current and R the resistance of the junctions [2]. In our samples the junctions are connected in a two-dimensional network (N junctions in parallel and M in series, so that $N_{TOT} = N \times M$). The radiation emitted by the array is detected on-chip with a nearby detector junction, as shown schematically in Fig. 1.
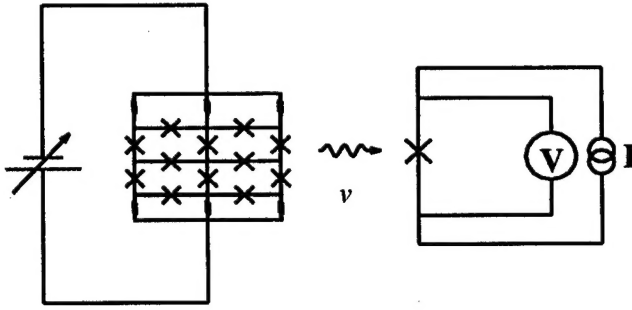

Fig. 1. Schematic representation of the array-detector operation. Radiation emitted by the array (at left) is detected by a single junction (at right).

When the detector junction is irradiated at frequency ν, steps at constant voltage appear on its IV curve. The step voltages are proportional to the frequency,

$$V_n = n\frac{h\nu}{2e}, \qquad (3)$$

where n is an integer. The step width is related to the power of the detected radiation (see Fig. 2).

Fig. 3 shows a schematic of our samples. The array is capacitively coupled to the detector junction, allowing both to be independently biased. A groundplane (not shown in Fig. 3) covers the entire structure. An actual array is shown in Fig. 4
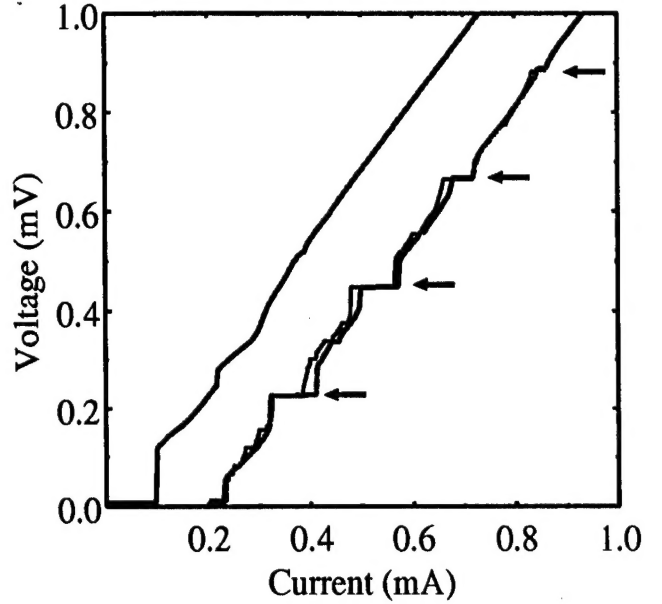

Fig. 2. Measured detector current-voltage characteristic showing emitted power at 105 GHz. Green curve is detector with array turned off, red curve is detector with array turned on, and black is simulation used to determine power. Arrows indicate Shapiro steps corresponding to $\nu = 105$ GHz.

This scheme was introduced in the first successful two-dimensional sources by S. P. Benz and C. J. Burroughs [7]. During our work we added substantial modifications to the original design.

1. We reduced the stray capacitance formed by the overlapping area between the ground-plane and one plate of the coupling capacitor. This change increased the maximum detected frequency from 280 GHz to 430 GHz. Our estimates of detected power (at frequencies corresponding to the best response of the detector junction) showed a 130% increase, from $0.13 P_{MAX}$ to $0.3 P_{MAX}$, coupled into the detector with the new design.

2. We started a detailed analysis of the frequency dependent transmission of the coupling circuit. This study is essential to estimate the actual power emitted by the array as a function of frequency. A substantial part of this work was done in collaboration with Dr. Shitov, who developed a program to simulate our arrays and coupling circuit. In the simulations the detailed dimensions
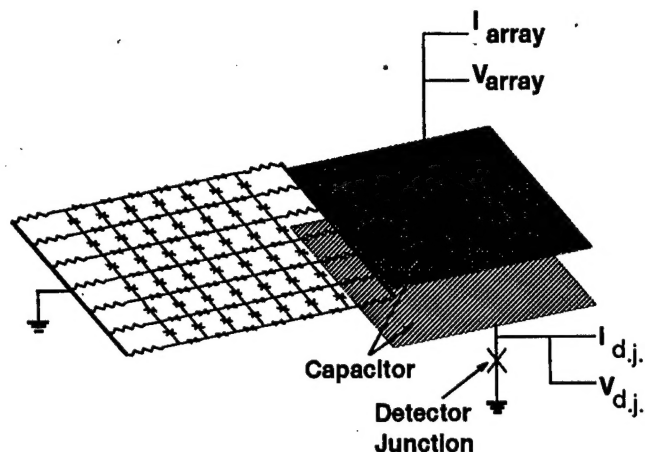
3

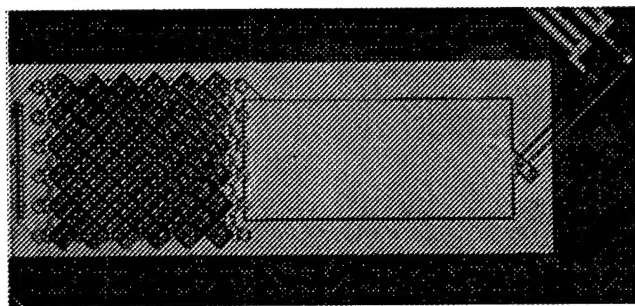Fig. 3. More detailed schematic of array and detector. Groundplane is omitted for clarity.

Fig. 4. Micrograph of the sample. Array (at left) is coupled through rectangular capacitor to detector junction (at right). Capacitor is 410 $\mu m \times$ 180 μm. Larger rectangle surrounding both array and capacitor is the groundplane.

of the superconducting films and thickness of the superconducting layers are taken into account and the whole structure is modeled via a combination of microstrip lines. In this linearized approach the junctions are represented by a parallel connection of tunnel resistance and capacitance.

Fig. 5 shows a plot of the calculated maximum power *coupled* into the detector (i.e. correcting the calculated maximum power *emitted* by the array with the transmission coefficient of the coupling circuit) as a function of frequency. The measured power agrees quite well with the calculated curve. The drastic drops in coupled power in Fig. 5 are due to undesired resonances in the coupling circuit. In the same figure the calculated maximum power *emitted* by the ar-
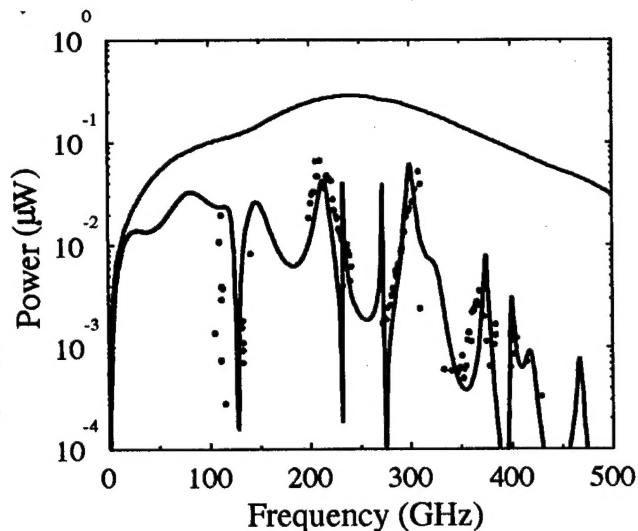

Fig. 5. Calculated (blue line) and experimental (green dots) power coupled into the detector as a function of frequency. The red line represents the theoretical maximum power emitted by the array.

ray is also shown. This plots show clearly that, in spite of the improvements described in 1., the performance of this coupling circuit is not satisfactory. Our new design contains changes in the dimensions of the coupling capacitor, high frequency filters and both SIS detectors and Josephson detectors. The calculated frequency dependence of the transmission in this circuit is shown in Fig. 6.
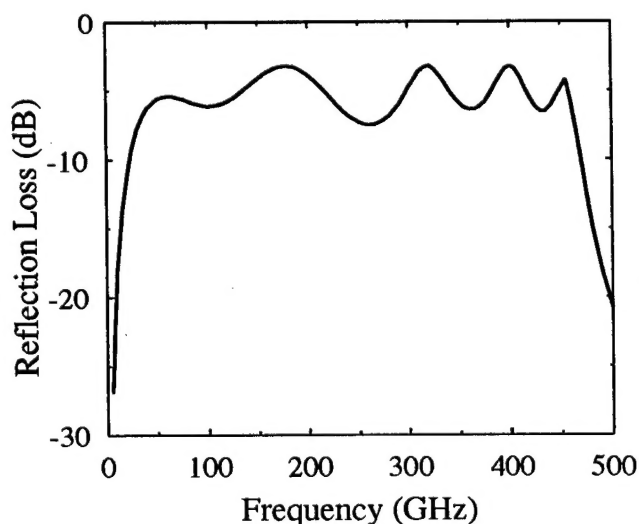

Fig. 6. Calculated frequency dependence of the transmission for the improved coupling circuit.

4

3. We began systematic modifications to the array characteristic parameters and design in order to obtained increased emitted power.

a. We measured arrays with different critical current densities (from 1 to 2.5 kA/cm^2). We detect increased power from the arrays with higher critical current. However, the tunability range drastically decreases, i.e. the high-I_C arrays emit only in the range 180-250 GHz. The optimum trade-off between tunability and higher power needs to be found.

b. By doubling the total number of junctions from 5 × 10 to 10 × 10 we doubled the power, as expected from Eq. (2). Our next goal is to maximize the number of junctions within this linear regime. This will probably require more compact geometries, in order to keep our device sufficiently *lumped* in the range of operating frequencies.

c. We changed the geometry of the shunt resistor in order to minimize the stray inductance associated with the shunt resistor. This inductance limits the high frequency performance of the array [7].

2) Underdamped Arrays: The underdamped two-dimensional arrays we analyzed were designed with the same geometry as the overdamped ones, the only difference being the removal of the shunt resistors. By measuring the current voltage characteristics of these arrays in the presence of a magnetic field (applied in the plane of the junctions), we found resonances appearing as sharp, constant voltage steps, corresponding to Josephson frequencies in the range 150-200 GHz. A detailed study of these steps showed that their voltage is independent of temperature, external magnetic field and number of junctions in the array. In fact, the voltage of these resonances seems only to depend on the distance d between the array and the ground-plane. A circuit analysis of these arrays, made with the same type of simulations described above, shows that the inductance of the microstrip line connecting neighbor junctions depends on d. This inductance resonates with the capacitance of the junction at frequencies that are very close to the Josephson frequencies corresponding to the measured step voltages. Resonances at similar values of frequency are also found in overdamped arrays, indicating that this mechanism might exist for both types of array.

Using a newly-designed coupling circuit and detector, we have also measured the radiation emitted by these underdamped arrays. The power detected from the resonant states increases by increasing the number of active junctions, up to array length comparable to the radiation wavelength. Moreover, the conversion efficiency from DC to AC power is about 15%, from a small array containing 108 junctions emitting 0.05μW of power. We have also studied larger arrays, with a maximum power detected being 0.12μW from an array with 690 junctions. Although there is scatter in the data, preliminary analysis indicates that there is a threshold number of junctions for power emission, and that above the threshold the power increases with the square of the number of junctions.

A possible explanation for these new experimental results is the occurrence of a travelling-wave coupling mechanism, where the lag in the oscillator phases matches the phase gradient of the travelling wave. However, some characteristics of these coherent states and their underlying coupling mechanism may not be completely explained by a classical electrodynamic description.
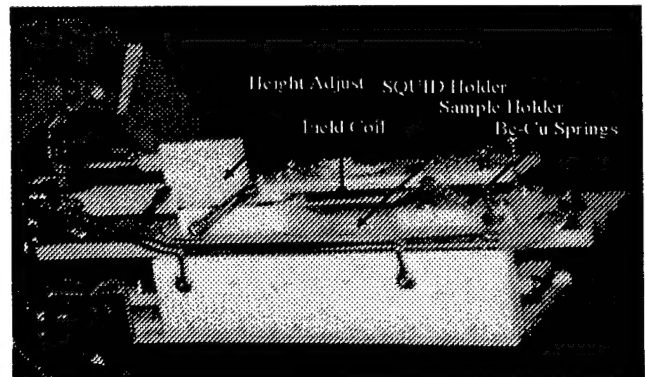

Fig. 7. Photograph of a Wellstood scanner. The top spring-loaded piece holds a copper coil (to provide a small magnetic field) and the SQUID, and can be adjusted vertically while cold. The sample holder below the SQUID is scanned in the horizontal plane.

3) Scanning SQUID Microscope: A low-temperature scanning SQUID microscope has been built, and has been successfully used to image a Josephson-junction array. (See Fig. 7) The SQUID clearly shows vortices trapped in the array, as well as interesting avalanche behavior as flux enters the sample. In addition, an AC technique has been used to monitor losses in the array.

4) FIR Laser Probe: We built a low temperature probe for shining far infrared radiation onto the arrays. The radiation is provided by a far-infrared laser, which is pumped by a CO_2 laser. This apparatus is available in the laboratory of Prof. H. D. Drew, and frequencies ranging from 150 GHz to 2.5 THz can be obtained. Our goal is to test the interaction between Josephson-junction arrays and the external radiation in a wide frequency range. Due the reciprocity of the Josephson relation, the frequency dependence of the synchronization of the junctions to external radiation should give us information about the possible achievable operating frequency range of the devices. Moreover, it will be possible to test the performance of arrays as on-chip local oscillators in SIS receivers.

REFERENCES

[1] B. D. Josephson, Phys. Lett. 1, 251 (1962).
[2] A. K. Jain, K. K. Likharev, J. E. Lukens, and J. E. Sauvageau, Phys. Reports, 109, 309 (1984).
[3] P. Booi and S. P. Benz, Appl. Phys. Lett., 68, 3799 (1996).
[4] K. Wiesenfeld, S. P. Benz and P. Booi, J. Appl. Physics 76, 3835 (1994).
[5] P. Hadley, M. R. Beasley and K. Wiesenfeld, Appl. Phys. Lett. 52, 1619 (1988).
[6] R. L. Kautz, IEEE Trans. Appl. Supercon. (proceedings APS 1994).
[7] S. P. Benz and C. J. Burroughs, Supercond. Sci. Technol. vol.4, 561 (1991).
[8] A. B. Cawthorne, P. Barbara and C. J. Lobb, High-Frequency Properties of Two-Dimensional Josephson-Junction Arrays, IEEE Trans. Appl. Supercon. 7, 3403 (1997).

C. Supplemental Information

1) Papers Acknowledging Grant Support:

1. M. Octavio, C. B. Whan, U. Geigenmüller, and C. J. Lobb, *Dynamical States of Underdamped Josephson Arrays in a Magnetic Field*, Phys. Rev. B 47 (Rapid Communication), 1141 (1993).
2. C. B. Whan, C. J. Lobb, and M. G. Forrester, *Effect of Inductance on Externally Shunted Josephson Tunnel Junctions*, J. Appl. Phys. 77, 382 (1995).
3. C. B. Whan and C. J. Lobb, *Complex Dynamical Behavior in RCL-Shunted Josephson Junctions*, IEEE Transactions on Applied Superconductivity 5, 3094 (1995) (Proceedings of the 1994 Applied Superconductivity Conference).
4. C. B. Whan, A. B. Cawthorne, and C. J. Lobb, *Synchronization and Phase Locking in Two-Dimensional Arrays of Josephson Junctions*, Phys. Rev. B 53, 12340 (1996).
5. C. J. Lobb and R. S. Newrock, *Ginzburg-Landau Theory for Three-Dimensional Josephson Junction Arrays*, J. Low Temp. Phys. 105, 133 (1996).
6. C. B. Whan and C. J. Lobb, *Complex Dynamical Behavior in RCL-Shunted Josephson Tunnel Junctions*, Phys. Rev. E 53, 405 (1996).
7. A. B. Cawthorne, P. Barbara and C. J. Lobb, High-Frequency Properties of Two-Dimensional Josephson-Junction Arrays, IEEE Trans. Appl. Supercon. 7, 3403 (1997).
8. A. B. Cawthorne, C. B. Whan, and C. J. Lobb, Influence and Evaluation of Parasitic Inductanc in Shunted Josephson Junctions, IEEE Trans. Appl. Supercon. 7, 2355 (1997).
9. F. M. Araujo-Moreira, P. Barbara, A. B. Cawthorne, and C. J. Lobb, Reentrant AC Magnetic Susceptibility in Josephson-Junction Arrays, Phys. Rev. Lett. 78, 4625 (1997).
10. R. D. Parmentier, P. Barbara, G. Costabile, A. D'Anna, B. A. Malomed, and C. Soriano, Flux-Flow Drag in Stacked Josephson Junctions, Phys. Rev. B 55, 15165 (1997).
11. A. B. Cawthorne, C. B. Whan, and C. J. Lobb, *Complex Dynamics of Resistively and*

Inductively Shunted Josephson Junctions, submitted to Journal of Applied Physics.

12. P. Barbara, F. M. Araujo-Moreira, A. B. Cawthorne, and C. J. Lobb, Reentrant AC Magnetic Susceptibility in Josephson-Junction Arrays: an alternative explanation for the paramagnetic Meissner effect, submitted to Phys. Rev. B, (1998).

2) Conference Presentations Acknowledging Grant Support:

1. M. C. Hernandez, M. Octavio, C. J. Lobb, D. B. Mast, and R. S. Newrock, *Noise in SNS Josephson Junction Arrays*, Bull. Amer. Phys. Soc. 40, 69 (1995).
2. C. B. Whan, A. B. Cawthorne, and C. J. Lobb, *Numerical Study of Phase-Locking Mechanisms in 2D Josephson Arrays*, Bull. Amer. Phys. Soc. 40, 117 (1995).
3. S. T. Herbert, Youngha Jun, D. B. Mast, R. S. Newrock, and C. J. Lobb, *Absence of the Kosterlitz-Thouless Transition in Two-Dimensional Josephson Junction Arrays*, Bull. Amer. Phys. Soc. 40, 119 (1995).
4. R. S. Newrock, L. B. Gomez, Said El-hamari, D. B. Mast, S. Herbert, and C. J. Lobb, *Ginzburg-Landau Theory for Three-Dimensional Josephson-Junction Arrays*, Bull. Amer. Phys. Soc. 41, 466 (1996).
5. A. B. Cawthorne, C. B. Whan, and C. J. Lobb, *Complex Dynamics of Resistively and Inductively Shunted Josephson Junctions*, Bull. Amer. Phys. Soc. 41, 532 (1996).
6. A. B. Cawthorne, P. Barbara, and C. J. Lobb,*High-Frequency Dynamics of Two-Dimensional Josephson Junction*, Arrays, Bull. Amer. Phys. Soc. 42, 185 (1997).
7. P. Barbara, A. B. Cawthorne, and C. J. Lobb, *High-Frequency Steps and Intrinsic Phase Locking in Two-Dimensional Arrays of Underdamped Josephson Junctions*, Bull. Amer. Phys. Soc. 42, 185 (1997).
8. F. M. Araujo-Moreira, P. Barbara, A. B. Cawthorne, and C. J. Lobb, *Dynamical Reentrant Behavior in χ_{AC} of Josephson-Junction Arrays*, Bull. Amer. Phys. Soc. 42, 186 (1997).

3) PhD Degrees Granted:

1. Chagarn Whan, 1995 (currently at IBM Watson Research Labs, Yorktown Heights, NY.)
2. A. B. Cawthorne, expected 1998.